Reprinted from Volume 12 of DEVELOPMENTS IN INDUSTRIAL MICROBIOLOGY
A Publication of the Society for Industrial Microbiology
AMERICAN INSTITUTE OF BIOLOGICAL SCIENCES • WASHINGTON, D.C. • 1971

CHAPTER 44

Microbial Susceptibility of Reticulated Polyester Urethane Foam in Simulated Fuel Tank Environments

MORRIS R. ROGERS AND ARTHUR M. KAPLAN

Pioneering Research Laboratory, U.S. Army Natick Laboratories, Natick, Massachusetts 01760

Open-celled, reticulated, low density polyurethane foam has found application in packing the fuel tanks of military and civilian aircraft, helicopters, and racing cars. The foam serves to prevent fuel vapor explosion in a fuel tank, acts as a fire retardant in post-crash situations, and also minimizes splashing and leaking of fuel from ruptured tanks. All previous reports dealing with microbial activity on polyester urethane foam in JP-4 systems have involved optimum levels of water or mineral salts solutions in order to encourage microbial growth. In simulated aluminum and steel fuel tanks containing foam and 1000:1 and 9:1 fuel/water ratios, microbial growth was found mainly restricted to the fuel/water interface. After nine months, significant losses were found in tear or tensile strengths of the foam in gasoline, JP-4, diesel, or CITE fuel/water environments. With the continued emphasis placed on good housekeeping and good fuel-handling practices, it would appear that plugging of the foam by microbial growth would occur only after continued disregard for established and proven fuel-handling practices.

INTRODUCTION

Considerable evidence is available to show that polyester urethane foams can support fungal growth (Edmonds and Cooney, 1968; Hedrick and Crum, 1968; Kaplan et al., 1968) and that under certain laboratory test conditions the microbial attack may cause physical damage to the foam (Hedrick, 1969). Hedrick (1970) also reported that the heaviest microbial growth and activity, resulting in degradation of the foam and corrosion of the aluminum alloys, were found in the tanks incubated under continuous agitation and that the degree of microbial activity was also influenced by the type of alloy present. Cooney (1969) and Cooney and Felix (1970) attempted to prevent fungal attack of the polyurethane foam by the incorporation of salts of 1-hydroxypyridine-2-thione into the foam polymer. However, after exposure for 90 days in a fuel/water environment, fungal development was as extensive in the foam containing the biocide additives as it was in the control foam samples containing no biocide. In spite of the laboratory evidence that shows foam is susceptible to microbiological attack, the military and others are incorporating the foam into fuel tanks of aircraft and other vehicles at an ever-increasing rate. For example, 36 USAF C-130E airplanes, now in production, will have the polyurethane foam baffles in their wing and pylon tanks. Retrofit of all C-130 airplanes is not anticipated; however, several C-130A and some special mission C-130E models have had foam installed as a modification (Anon., 1969). The foam is also in use in C-123, C119, F105, F-4, C-47, OV-10, and O-2 airplanes.

To the best of our knowledge, no failures due to microbiological breakdown of the foam have been reported by any of the military users in the field. A total of over three

years of satisfactory service experience has been accumulated on the present fuel tank foam by the Air Force. These include an F-105, C-130, and B-52 aircraft. In addition, considerable experience with the foam in combat-type aircraft stationed in the Southeast Asia environment has been developed (Reed, 1970). It is also our understanding that the foam has been used in the fuel tanks of racing cars for five years without incident. It would appear, from the lack of any fuel problems reported from the field, that recommended good housekeeping practices together with the continued use of the anti-icing additive in JP-4 fuel (Anon., 1964) have nearly eliminated microbial problems in JP-4 fuel systems. This includes those systems with polyester urethane foam. The combined effects of eliminating water from the fuel system and the biocidal properties of the anti-icing additive appear responsible for the lack of fuel problems. Previous reports dealing with microbial activity on polyester urethane foam in JP-4 fuel systems have involved optimum levels of water or mineral salts solution in order to encourage microbiological growth. The purpose of this work was to evaluate the extent of microbial growth in a foam/fuel/water environment where the water phase was minimal. This was done in an attempt to simulate water contamination levels that are more realistic and in agreement with those values maintained in aircraft or vehicle fuel tanks operated under good housekeeping practices.

Materials and Methods

In order to duplicate more nearly the actual use conditions, metal testing tanks measuring 5.5 inches by 9 inches and 6 inches high (Fig. 1) were fabricated from low carbon steel (Anon., 1961) and aluminum (Anon., 1962). Each test tank was filled with a 5.5 × 8 × 4 inch wedge of LAS-103Z7 (10 pores per inch) orange polyester urethane foam furnished by Firestone Coated Fabrics and 2 liters of fuel, either diesel, CITE (Compression Ignition Turbine Engine), JP-4, or regular gas. Bushnell-Haas (1941) salt solution (2 ml) was added to give a 1000:1 fuel/water ratio. Each tank was inoculated with a mixed inoculum consisting of three strains of the fuel-

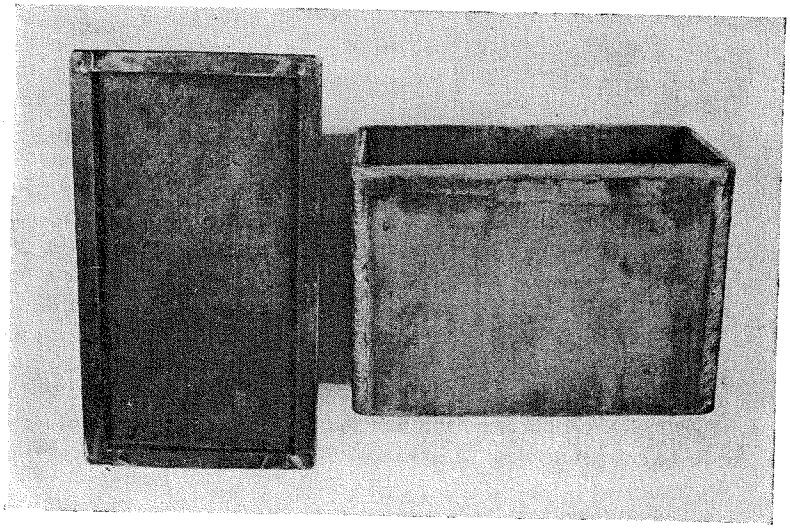

Fig. 1. Unassembled steel test tank with cover plate on left.

utilizing fungus, *Cladosporium resinae*, QM 7998, QM 7978, and QM 8012; *Pseudomonas putida*, Army No. 29 (isolated from a JP-4 filter separator); and the six organisms recommended by the American Society for Testing and Materials (Anon., 1963) for the determination of the susceptibility of plastics and plastic-like materials to mold growth. This latter group of organisms included *Aspergillus niger* QM 386, *A. flavus* QM 380, *A. versicolor* QM 432, *Penicillium funiculosum* QM 391, *Pullularia pullulans* QM 279c, and *Trichoderma* sp. QM 365 with the addition of *Chaetomium globosum* QM 459 (Darby, 1967). Darby (Unpublished data, 1968) found that the orange polyester urethane foam would readily support the growth of the ASTM mixture supplemented with *C. globosum* using the mixed culture Petri dish method. A second set of tanks was prepared in which the fuel/water ratios were more conducive to microbial growth. These tanks were treated as above except that the fuel/water ratio was changed to 9:1 (1800 ml fuel:200 ml Bushnell-Haas solution). Control tanks of diesel fuel without Bushnell-Haas solution were also employed. All tanks were covered and incubated under static conditions at 30 C for nine months. Since others (Edmonds and Cooney, 1968; Hedrick and Crum, 1968; Hedrick, 1969; Cooney and Felix, 1970) have shown that *Pseudomonas* species proliferate in a fuel/mineral salts/polyurethane foam environment, no growth rate curves were developed for these experiments. Fungal growth was estimated by visual observation of the development of a mycelial mat.

At the end of incubation for nine months, the slabs of polyester urethane were removed from the tanks, cut into an appropriate thickness with the aid of a band saw, and specimens were stamped out with a die approximating the required shape and dimensions. Tear resistance specimens measured 1 × 1 × 6 inches and tensile specimens measured 1 × 0.5 × 5.5 inches as specified in Anon. (1967, 1968). All physical tests of the foam were determined on an Instron tester at a speed of 20 ± 1 inch/min for the tensile tests and a cross-head speed of 2 inches/min for the tear tests.

Results

Visual signs of microbial growth first appeared on the foam at the interface of the fuel/water layer after one week of incubation. The growth was estimated to have reached its maximum after one to two months incubation in three of the four fuels tested. The greatest growth appeared on the foam exposed in the aluminum tank with the 9:1 fuel/water ratios. CITE fuel appeared to provide the heaviest growth observed. The amount of growth on the foam exposed in the 1000:1 fuel/water ratios was scanty and appeared only in isolated areas on the bottom of the foam, adjacent to the droplets of water found on the bottom of the tanks. The growth noted on the foam exposed in the steel tanks appeared dark due to rust and scale formation, as shown in Figure 2. An aluminum tank with copious amounts of fungal slime and some corrosion products is shown in Figure 3. Figures 4-15 show a comparison of the extent of visual microbial growth on the foam observed in the 9:1 and the 1000:1 fuel/Bushnell-Haas dilutions. The diesel fuel also stained the foam a brownish color irrespective of microbial growth. No growth was observed on the foam or at the fuel/water interface in the tanks containing regular gasoline. In no instance was the microbial growth so massive that it caused a continuous mycelial plug across the fuel/water interface.

The tensile and tear strength of the foams after exposure for nine months in 1000:1 and the 9:1 fuel/Bushnell-Haas medium are shown in Table 1. The minimum tensile strength

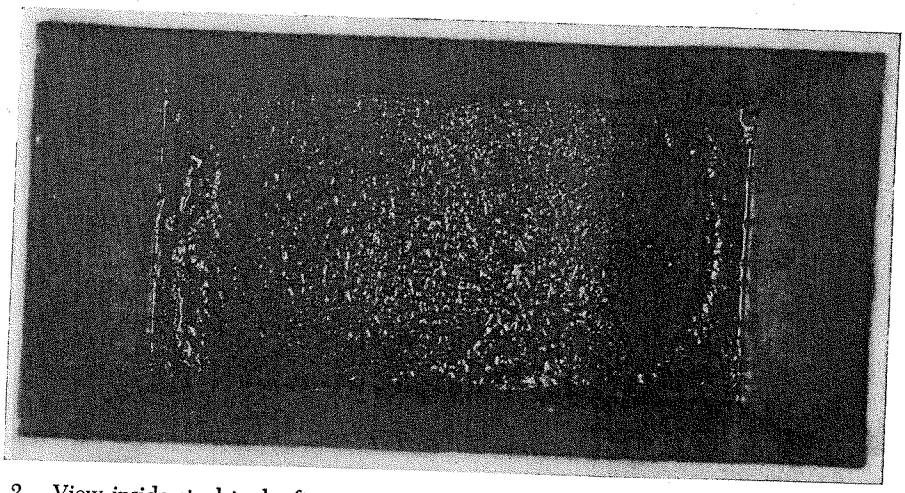

FIG. 2. View inside steel tank after exposure for nine months to an inoculated 9:1 JP-4/Bushnell-Haas/foam environment showing large masses of rust on the bottom of the tank.

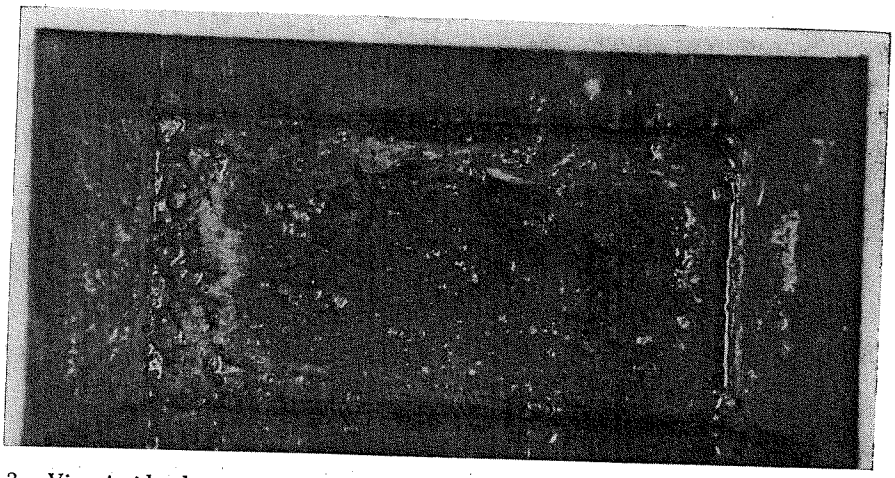

FIG. 3. View inside aluminum tank after exposure for nine months to an inoculated 9:1 CITE fuel/Bushnell-Haas/foam environment showing mycelial slime and corrosion.

permitted by the foam specification (Anon., 1968) is 15 psi, with a 20% deviation from the average. The tensile data suggest that the foam has fallen below the minimum levels permitted at time of manufacture. The tear strength for most of the test specimens remains above the 5 lb./inch minimum required by the specification. However, in the 1000:1 fuel/Bushnell-Haas systems, there were three instances where the below minimum tear strength ranged between 4.5 and 4.7 lb./inch, and between 3.4 and 4.7 lb./inch with 9:1 fuel/Bushnell-Haas systems. The noticeable drop in the zero time tensile strength of the foam samples, from before to after conditioning in the various test fuels, is difficult to explain. The most plausible explanation is that it is a result of test repeatability as well as specimen variation and preparation, as previously reported by Gibson et al. (1966).

TABLE 1. *Average tensile and tear strength of polyester urethane foam after exposure for nine months in 1000:1 and 9:1 fuel/Bushnell-Haas medium*

Tensile (psi)

deviation minimum f the test ion. How- where the tween 3.4 op in the ing in the is that it aration, as

9:1 CITE

P-4/Bush- nk.

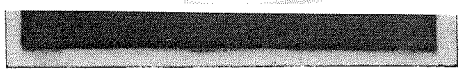

TABLE 1. *Average tensile and tear strength of polyester urethane foam after exposure for nine months in 1000:1 and 9:1 fuel/Bushnell-Haas medium*

	Tensile (psi)						Tear (lbs. per inch)					
Fuel:Water Ratios	Zero Time (Before Conditioning)	Zero Time (After Conditioning[a])	Aluminum Tanks (Fuel Interface)		Steel Tanks (Fuel Interface)		Zero Time (Before Conditioning)	Zero Time (After Conditioning)	Aluminum Tanks (Fuel Interface)		Steel Tanks (Fuel Interface)	
JP–4												
1000:1	20.17	14.6	10.8	11.0	11.4	11.0	7.23	6.6	4.5	5.0	5.3	5.4
9:1			11.8	13.8	12.8	11.4			6.3	5.6	6.5	5.3
CITE												
1000:1		14.8	11.8	12.2	13.6	12.4		6.5	6.3	4.7	5.8	5.4
9:1			10.6	9.2	17.6	13.2			5.1	3.4	4.5	6.6
Diesel												
1000:1		14.2	13.0	12.8	11.8	12.2		6.5	6.5	5.8	6.0	4.7
9:1			9.0	9.8	9.2	10.4			5.3	4.7	5.0	4.7
Regular gas												
1000:1		15.6	11.2	11.8	12.2	10.8		6.2	5.4	5.6	5.3	5.9
9:1			11.0	9.6	13.2	10.4			4.9	4.7	5.9	5.4
Uninoculated Diesel												
1000:1		14.2	10.6	12.0	12.0	10.0		6.5	5.0	3.8	5.8	4.8
9:1			11.2	12.2	14.4	12.2			5.4	4.2	7.3	6.2
Samples soaked four days and broken wet	20.17		Gas 12.43	CITE 14.75	JP–4 15.75	Diesel 18.12	7.23		Gas 5.5	CITE 7.1	JP–4 7.4	Diesel 6.7

[a] Soaked in fuel four days and dried overnight before breaking.

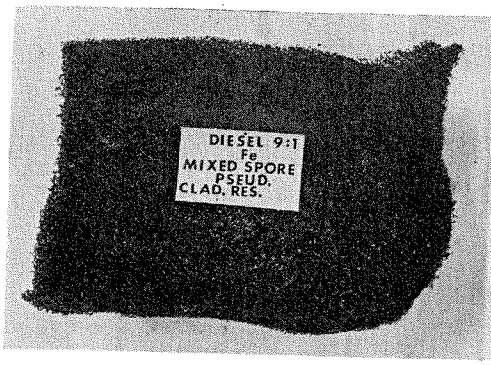

FIG. 4. Side view of foam exposed for nine months in an inoculated steel tank containing 9:1 diesel fuel/Bushnell-Haas medium. Isolated areas of microbial slime are visible within the foam area darkened by the diesel fuel.

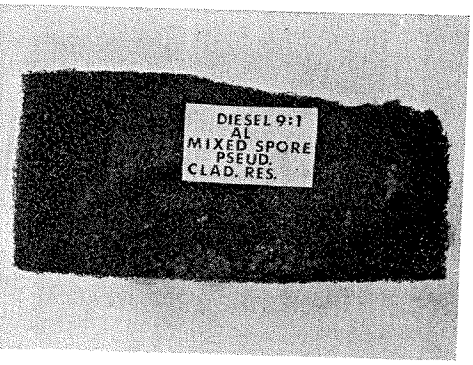

FIG. 5. Bottom view of foam exposed for nine months in an inoculated aluminum tank containing 9:1 diesel fuel/Bushnell-Haas medium. Foam has turned a dark brown and areas of microbial attachment are visible.

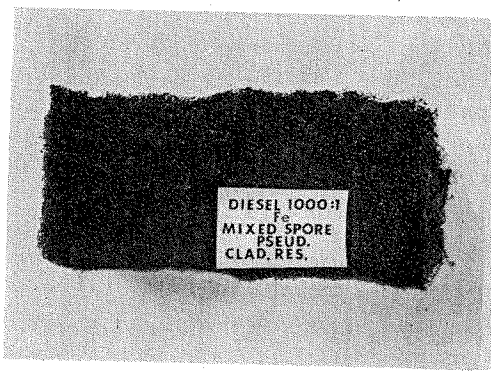

FIG. 6. Bottom view of foam exposed for nine months in an inoculated steel tank containing 1000:1 diesel fuel/Bushnell-Haas medium. Foam has been darkened by the fuel and only scattered areas of rust and/or microbial involvement are visible.

FIG. 7. Bottom view of foam exposed for nine months in an inoculated aluminum tank containing 1000:1 diesel fuel/Bushnell-Haas medium. Foam has been darkened by the fuel and only scattered areas of microbial attachment are visible.

DISCUSSION

Test Procedures

The satisfactory performance of the foam in aircraft after service for three years in the United States and Vietnam would indicate there is little relationship between the laboratory test results reported by Hedrick and Crum (1968), which showed a decrease of 60 to 70% in the tensile strength of the foam after exposure to *C. resinae* for 60 to 90 days, and actual field experience. Although our experiments did not confirm the extremely high losses in tensile strength and fragmentation of the foam reported by Hedrick and Crum, they did show significantly high tensile and tear losses of the exposed foam. It is important to provide some explanation as to the cause for the wide divergence between laboratory test results and field experience with the foam.

It is believed (Rogers and Kaplan, 1968) that the crucial test in the development of

FIG. 8. Bottom view of foam exposed for nine months in an inoculated steel tank containing 9:1 CITE fuel/Bushnell-Haas medium. Foam shows some isolated areas of microbial slime.

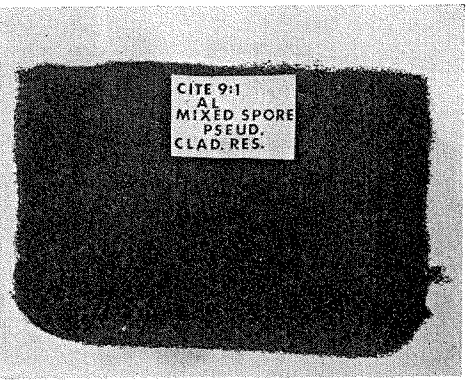

FIG. 9. Side view of foam exposed for nine months in an inoculated aluminum tank shown in Figure 3, containing 9:1 CITE fuel/Bushnell-Haas medium. Foam shows a heavy, dark mycelial mat at the interface and invasion of the center portion of the foam exposed to the fuel layer.

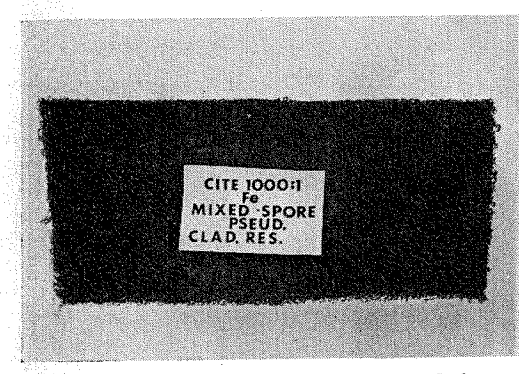

FIG. 10. Bottom view of foam exposed for nine months in an inoculated steel tank containing 1000:1 CITE fuel/Bushnell-Haas medium. Foam shows only isolated areas of microbial growth and rust.

FIG. 11. Bottom view of foam exposed for nine months in an inoculated aluminum tank containing 1000:1 CITE fuel/Bushnell-Haas medium. Foam shows only isolated areas of microbial growth and discoloration.

an experimental material, such as polyurethane foam, is its effectiveness in a full-scale field exposure. Here close observation and careful analysis are possible under conditions which arise in practice. The laboratory test should be designed to include, as nearly as possible, the conditions which exist or are likely to exist in the field. This, of course, is easier to state than to carry out in practice. Although most persons in the applied areas of microbiology attempt to accomplish this in laboratory evaluation of microbial problems, it is also necessary to have experimental conditions in the laboratory which differ from the wide spectrum of field conditions in order to meet workable and practical laboratory limitations.

One of the limitations in the work reported by Hedrick and Crum (1968) and by Cooney (1969) is the use of a mineral salts layer which is far in excess of the water layer normally found in aircraft fuel tanks. With the continued emphasis placed on good housekeeping and good fuel-handling practices, water is not allowed to accumulate

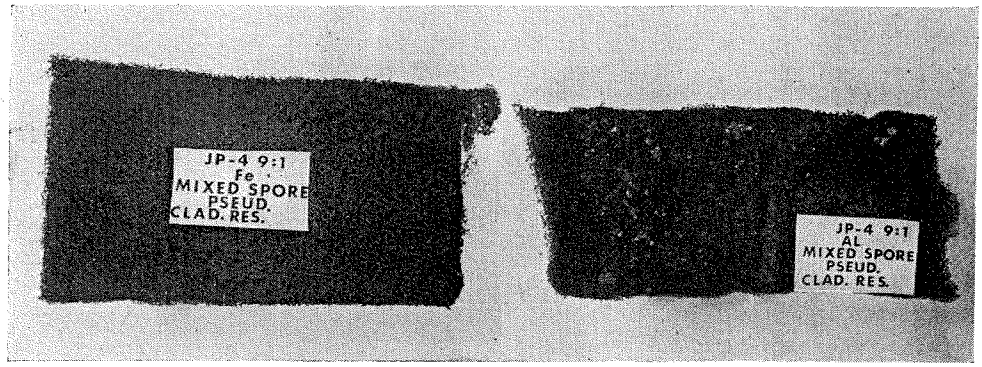

FIG. 12. Bottom view of foam exposed for nine months in an inoculated steel tank shown in Figure 2, containing 9:1 JP-4/Bushnell-Haas medium. Foam shows considerable darkening due to rust and microbial growth.

FIG. 13. Bottom view of foam exposed for nine months in an inoculated aluminum tank containing 9:1 JP-4/Bushnell-Haas medium. Foam shows areas of microbial attachment.

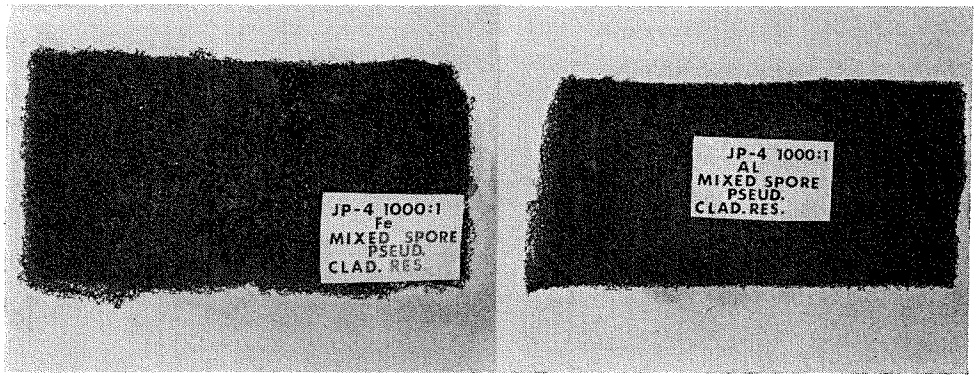

FIG. 14. Bottom view of foam exposed for nine months in an inoculated steel tank containing 1000:1 JP-4/Bushnell-Haas medium. Foam shows area of discoloration due to rust and microbial attachment.

FIG. 15. Bottom view of foam exposed for nine months in an inoculated aluminum tank containing 1000:1 JP-4/Bushnell-Haas medium. Foam shows no visual signs of microbial involvement.

in the fuel tanks except for small puddles which cannot be drained because of the wing design. Therefore, the fuel/water ratio in operating aircraft (except for the sump areas) is normally somewhere in the 1000:1 range or less. Attempting to carry out bacterial growth curves using these ratios would be pointless in a laboratory because of insufficient water present for optimum growth plus the absence of adequate water for sufficient sampling to monitor the rate and amount of growth. Therefore, Hedrick and Crum (1968) and Cooney (1969) were forced to use unrealistic amounts of mineral salts medium, which simulates the water present in a fuel tank, in order to develop the needed growth curve data for some of the bacteria which utilize fuel. The same general reasoning applies to the fuel-utilizing fungus, *C. resinae*.

Hedrick (1969) also showed that the heaviest microbial growth and activity resulting in degradation of the foam and corrosion of the aluminum alloys occurred during continuous agitation. The agitation tends to simulate the motion of fuel in the tank of an operating aircraft better than a static test and undoubtedly allows for better gaseous

exchange. However, the applicability of this test to a normal use situation is open to question since there would not be sufficient water present to permit the type of growth observed. Nevertheless, this experiment clearly shows that if the aircraft fuel environment is permitted to accumulate high levels of water, the foam present in the tank may readily support, and be penetrated by, microbial growth.

An additional testing procedure which must be carefully evaluated as a tool for measuring the microbial degradation of foam is the tensile strength test. The large variability in tensile strength often experienced in samples selected from the same bun of foam is indicative that this is not the most critical test for evaluating microbial degradation of foam. Sample preparation is extremely important and probably accounts for much of the variability experienced in using foam. It can also be easily visualized that, in a foam produced in accordance with Military Specification Mil-B-83054 (Anon., 1968), specifying 10 pores/inch but permitting variation of +5 to −3 pores/inch, it is very difficult to prepare a dumbbell specimen for tensile testing with a uniform number of pores/inch. This lack of uniformity in pore size is reflected in the high variability obtained in attempting to determine the tensile and tear strength of the foam. Sample preparation and the use of a special die for stamping out the tensile specimens is a critical step in testing a material with inherent high variability in physical properties.

An additional complicating factor is the volume swell of the foam after it is exposed to fuel. The volume increase may be as high as 5%, depending on the fuel, temperature, and length of exposure. Consequently, a specimen removed from the foam after exposure in a fuel environment will have less pores/inch than before exposure. The smaller number of pores/inch will be reflected in a lowering of tensile and tear strength. Therefore, tensile and tear strength data, as a measurement of microbial damage to the foam, can at present only be considered a tenuous indicator. The variability in the foam is much larger than one would normally expect, and the applicability of the ASTM D-1564-64T (Suffix T) method (Anon., 1967) as a sensitive test for measuring biodegradability with good reproducibility is open to question.

The foam is subject to some chemical instability after manufacture. For example, additional cross-linking of the polyester takes place during storage which results in a change in the physical charcteristics of the foam, including tensile strength. In contrast, foams stored under high humidity/temperature conditions are subject to hydrolysis. The polyester-type urethane rubbers are particularly susceptible to moisture vapor-induced hydrolysis consisting of scission of the main chain ester groups resulting in reversion of the foam, with subsequent breakdown of the polymer through fungal activity. Evidence is also available which shows that a volume mixture of 25% anti-icing additive without glycerine (Anon., 1964) for JP-4 fuel and distilled water caused a drop in tensile strength from 25 psi to 1.3 psi, after 12 days at 70 C.

Conclusions

The above studies clearly illustrate problems associated with the microbiological testing of polyester urethane foam. In dealing with commercial materials, the microbiologist is often placed in a difficult position when determining whether or not a material is degraded by microorganisms. He is often required to assess microbial degradation in terms of damage to, or changes in, the physical and chemical characteristics of a material with only limited technical information about the material in question. It is incumbent upon the microbiologist to know as much as possible about the material he

is evaluating. However, it is often difficult to obtain knowledge of the many details and limitations of the technical characteristics and properties of the material because they are proprietary in nature or because the material is still in the development stage where the requirement limits have not been established for all its properties. Thus, microbial degradation data on a material accumulated in the early stages of development and production do not necessarily apply to current production lots. It is unlikely that each time a production change is made in the composition, source of ingredients, and processing technique for the commercial material that adequate precautions have been taken to determine its resistance to microbial attack. Therefore, no blanket endorsement can be given to a material regarding its microbial susceptibility unless every component and processing technique is known and specified in detail. It is doubtful, however, that such detailed information will be disclosed to the microbiologist since the development technology is continually changing and the microbiologist is usually brought into the picture after the change has been instituted.

In considering the variables which might contribute to increased microbial degradation of materials such as polyester urethane foam, it is important that the variables be introduced into the experiment so that they tend to reflect the use situation. If the information obtained from such experiments is to be used in rendering a decision on whether or not a material should go into production, the producer must interpret the data in light of the details of the tests and their limitations.

In fuel tanks which by design do not permit easy access and draining of accumulated water, the foam may theoretically concentrate nutrients by acting as an absorbing surface for nitrogen compounds, carbon dioxide, and other nutrients. Growth appears at the interface because of the concentration of food elements at this site that normally are much more dilute and more widely dispersed. Thus, the use of foam in areas where water cannot be drained from the fuel tanks only compounds a potentially serious microbiological picture.

On the other hand, in a system where good fuel-handling procedures are maintained under good housekeeping standards which minimize water levels, the introduction of the foam is not likely to present any added microbiological burden. The added biocidal properties of the anti-icing additive in JP-4 fuel would bolster the odds against having a microbial problem. The possibility of incorporating a compatible and effective fungicide in the foam would theoretically give added protection to the foam in the case of a breakdown in the fuel-handling procedures. While the potential dangers associated with jet fuel are much greater than those of other distillate fuels (Rogers and Kaplan, 1968), problems encountered in the latter case can be extremely costly to military and commercial consumers. With the continued emphasis placed on good housekeeping and good fuel-handling practices, it would appear that microbial problems with fuels, or foam used in conjunction with fuels, arise only after disregard for established and proven fuel-handling practices.

The practical usefulness of much of the data available on the microbial susceptibility of the polyurethane foam for fuel tanks is that it serves as a reminder that the microbial problem is always present. When water contamination is permitted to reach levels which do not reflect good fuel-handling practices, the foam can serve as a matrix for additional microbial growth. If conditions are permitted to deteriorate to this degree, it probably makes little difference whether or not the foam is present except to complicate the clean-up procedure which must follow. One such procedure, of course, is to remove the water from the system and to add a biocide to the fuel. The selection of the biocide for this system, however, may not be simple since it must not cause degradation of the foam.

LITERATURE CITED

Anon. 1961. Federal Specification QQ-S-698. Steel, sheet, and strip, low-carbon.

Anon. 1962. Federal Specification QQ-A-00250/14a. Aluminum alloy B7178-T651, plate and sheet (supersedes Mil-A-9180, B7178-T651).

Anon. 1963. American Society for Testing Materials. Recommended practice for determining resistance of plastics to fungi. ASTM Designation D1924-63.

Anon. 1964. U.S. Government Printing Office. Military Specification Mil-I-27686. Inhibitor, fuel system icing. Washington, D.C. 4 p.

Anon. 1967. American Society for Testing Materials. Testing flexible urethane foam. ASTM Designation D1564-64T.

Anon. 1968. U.S. Government Printing Office. Military Specification Mil-B-83054. Baffle Material, Aircraft fuel tank. Washington, D.C. 15 p.

Anon. 1969. Polyurethane foam foils fuel vapor explosions. *Airlifters*, **3**: 13-14.

Bushnell, L. D., and H. F. Haas. 1941. The utilization of certain hydrocarbons by microorganisms. *J. Bacteriol.*, **41**: 653-673.

Cooney, J. J. 1969. Effects of polyurethane foams on microbial growth in fuel-water systems. *Appl. Microbiol.*, **17**: 227-231.

Cooney, J. J., and J. A. Felix. 1970. Polyurethane foams and foam additives in hydrocarbon fuel-water systems. *Develop. Ind. Microbiol.*, **11**: 210-224.

Darby, R. T. 1967. Testing cellulose-containing plastics for resistance to fungi. *Int. Biodetn. Bull.*, **3**: 65-66.

Darby, R. T., and A. M. Kaplan. 1968. Fungal susceptibility of polyurethanes. *Appl. Microbiol.*, **16**: 900-905.

Edmonds, P., and J. J. Cooney. 1968. Microbial growth in a fuel-water system containing polyester urethane foam. *Appl. Microbiol.*, **16**: 426-427.

Gibson, J. R., D. B. Nelson, R. A. Anduze, and J. C. Harris. 1966. Investigation of polyurethane foam for aircraft fuel system applications ASJ-TM-66-1. Wright-Patterson Air Force Base, Ohio.

Hedrick, H. G. 1969. Microbial activity on a polyurethane foam in jet-fuel-tank fluid systems. *Develop. Ind. Microbiol.*, **10**: 222-227.

———. 1970. Observations of microbial growth on polyurethane foam in aluminum alloy tanks. *Develop. Ind. Microbiol.*, **11**: 163-172.

Hedrick, H. G., and M. G. Crum. 1968. Effects of jet-fuel microbial isolates on a polyurethane foam. *Appl. Microbiol.*, **16**: 1826-1830.

Kaplan, A. M., R. T. Darby, M. Greenberger, and M. R. Rogers. 1968. Microbiological deterioration of polyurethane systems. *Develop. Ind. Microbiol.*, **9**: 201-217.

Reed, T. O. 1970. U.S.A.F. experience with polyurethane foam inerting material. Technical Memorandum ASNJI-TM-70-2. Wright-Patterson Air Force Base, Ohio.

Rogers, M. R., and A. M. Kaplan. 1968. Screening of prospective biocides for hydrocarbon fuels. *Develop. Ind. Microbiol.*, **9**: 448-476.